LHC Searches & Higgs Results

Andre Sznajder (UERJ)
Outline

✦ Standard Model
✦ The LHC and Experiments
✦ SM Higgs search
  • decays into bosons
  • decays into fermions
  • high mass exclusion
✦ Higgs properties
  • mass
  • couplings
  • spin & parity
  • width
✦ BSM Higgs search
✦ Future Perspectives
On July 4th 2012 ATLAS and CMS collaborations announced the discovery of a new boson around 125GeV.

Results followed by updates focusing on answering the questions:
- if the new boson is “the Standard Model Higgs boson”
- if there are any hints for the physics beyond SM?

Answers provided as:
- measurements of the new boson properties: mass, spin-parity ...
- searches for additional Higgs like bosons in a wide mass range

**ATLAS:** Phys.Lett. B716 (2012) 1-29

Electroweak Theory

In the mid 60’s Glashow-Salam-Weinberg proposed a unification of the weak and electromagnetic interactions based a SU(2)\textsubscript{L} × U(1)\textsubscript{Y} gauge theory

- fermions are doublets or singlets under SU(2)\textsubscript{L}
- Z and γ emerge as a mix of the two groups gauge fields
- Lagrangian contains neutral current as well as charged describing, e.g., beta decay and neutrino scattering

Weak interaction is short ranged => W and Z bosons are massive

**problem:** mass terms (m\textsubscript{W}^2 W^+\textsubscript{μ} W^-\textsubscript{μ}) break gauge invariance => loss of renormalizability and unitarity
The Higgs/BEH Mechanism

Problem of gauge bosons masses solved by Spontaneous Symmetry Breaking (SSB) mechanism elaborated by several authors at the beginning of the 60s


The Higgs Mechanism

The Higgs Mechanism applied to the SU\textsubscript{L}(2)\times U\textsubscript{Y}(1) local gauge theory is able to give mass to the gauge bosons

- gauge symmetry of the model is preserved while ground state of the scalar field “spontaneously” breaks the symmetry

- minimal solution uses a doublet of complex scalar fields ( 4 degrees of freedom ) – and has a non-zero vacuum expectation value(VEV)

- one component corresponds to an electrically neutral scalar particle – the “Higgs boson”

- remaining three components add a new degree of freedom (longitudinal polarization) of massive W\textsuperscript{±} and Z bosons

\[ m_H = \sqrt{2\lambda}v \]
\[ m_W = \frac{1}{2} \frac{ev}{\sin^2 \Theta_W} \]
\[ m_Z = \frac{1}{2} \frac{ev}{\sin \Theta_W \cos \Theta_W} \]
\[ m_\gamma = 0 \]
The Standard Model

The SM reflects our current understanding of elementary particles and the forces acting between them (with the exception of gravity).

**Matter**
- three generations of fermions
- in each generation
  - 2 quarks ($Q = +2/3, -1/3$)
  - 1 charged lepton ($Q = -1$)
  - 1 neutrino ($Q = 0$)

**Forces**
- the strong force (8 gluons)
- the electromagnetic force (photon)
- the weak force ($W, Z$)

Higgs field gives mass to electroweak gauge bosons and fermions (Yukawa couplings)
Why is the Higgs important?

The Higgs boson presents much more than just another new particle. It is a fundamental component of the standard model!

✦ the SM accurately describes decades of experimental measurements but its conceptual basis rely on the Higgs mechanism
✦ it describes the way elementary particles acquire mass. In a world with massless fermions atoms would not exist, the electron would be massless!!!

It changes our view on the nature of elementary particles

✦ mass is no more an intrinsic property of particle. It’s rather a result of an interaction with an external field!
✦ “break the paradigm” that interactions are dictated by gauge symmetries
SM Lagrangian

- Higgs mass is a free parameter of the model
- If we know the mass all Higgs interactions to elementary particles are determined by the model
- Higgs to fermions Yukawa couplings introduced by hand
Higgs Boson Interactions

Directly couple with the mass of elementary particles

$$f \rightarrow H = -i \frac{m_f}{v}$$

$$\bar{f} \rightarrow H$$

$$\mu$$

$$\nu$$

$$H = 2i \frac{M_Y^2}{v} g^{\mu\nu}$$

Self couplings

$$H = -3i \frac{M_Y^2}{v}$$

$$H \rightarrow H'$$

$$H \rightarrow H$$

$$2i \frac{M_Y^2}{v^2} g^{\mu\nu}$$
Couplings to Massless Bosons

Takes place through loops of massive particles

all fermions contributes, but top quark dominates due to its large mass

Opposing effects (interference)
Indirect Higgs Measurements

Until LHC, the only way to observe the Higgs boson has been through indirect measurements, i.e. to see its loop effects on other SM quantities. Find $m_H$ bounds from best Standard Model fits to all existing data. Quadratic dependence on $m_t$ but only logarithmic dependence on $m_H$ still precision measurements gives some sensitivity.
LHC

The world’s most powerful accelerator

- located at CERN near Geneva
  - ring of 27 km circumference and 100m bellow surface
  - can provide p-p, Pb-Pb (and p-Pb) collisions in 4 interaction regions
  - 1232 superconducting dipoles (−271.25°C)
  - UHV beam pipes as empty as interplanetary space (10^{-13} atm)

- p-p operation in 2012
  - CMS energy \( \sqrt{s} = 8 \text{TeV} \)
  - \( \approx 1400 \) bunches / beam with 50ns bunch spacing
  - peak luminosity of \( 7 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1} \) (10^9 collisions / s)

\[
L = \frac{N_b^2 n_b f_{\text{rev}} \gamma_r}{4 \pi \varepsilon_n \beta^*} F
\]

- \( N_b \) = number of proton per bunch
- \( n_b \) = number of bunches
- \( f_{\text{rev}} \) = rotation frequency (\( \sim 11 \text{Hz} \))
- \( F \) = crossing factor
- Rms transverse beam size = \( \sqrt{\varepsilon \beta / \gamma} \)
- \( \varepsilon_n \) = renorm. transverse emittance
- \( \beta^* \) = optics at beam crossing (m)
- \( \gamma_c \) = relativistic factor
LHC Experiments

- General purpose experiments: ATLAS and CMS (cover wide range of physics from SM measurements to BSM)
- Specialized experiments: Alice (heavy ions) and LHCb (B physics) ...
ATLAS & CMS Experiments

**ATLAS**
- Weight: 7000t
- Diameter: 22 m
- Length: 46 m
- Magnetic field: 2 T

**CMS**
- Weight: 12500t
- Diameter: 15 m
- Length: 22 m
- Magnetic field: 4 T

---

**ATLAS Detector Characteristics**
- Width: 44 m
- Diameter: 22 m
- Weight: 7000t

**CMS Detector**
- Total weight: 14,000 tonnes
- Overall diameter: 15 m
- Overall length: 28.7 m
- Magnetic field: 4 T

---

**Additional Details**
- **Muon Detectors**
- **Electromagnetic Calorimeters**
- **Solenoid**
- **Forward Calorimeters**
- **End Cap Toroid**
- **Barrel Toroid**
- **Inner Detector**
- **Hadronic Calorimeters**
- **Shielding**
- **Steel Return Yoke**
- **Silicon Trackers**
- **Superconducting Solenoid**
- **Fresnel**
- **Forward Calorimeter**
- **Muon Chambers**
- **Crystal Electromagnetic Calorimeter (ECAL)**
- **Hadron Calorimeter (HCAL)**

---

**CERN - ATLAS V1997**
## ATLAS vs CMS

<table>
<thead>
<tr>
<th></th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Magnetic field</strong></td>
<td>2 T solenoid + toroid (0.5 T barrel 1 T endcap)</td>
<td>4 T solenoid + return yoke</td>
</tr>
<tr>
<td><strong>Tracker</strong></td>
<td>Si pixels, strips + TRT</td>
<td>Si pixels, strips</td>
</tr>
<tr>
<td></td>
<td>$\sigma/p_T \approx 5\times10^{-4}p_T + 0.01$</td>
<td>$\sigma/p_T \approx 1.5\times10^{-4}p_T + 0.005$</td>
</tr>
<tr>
<td><strong>EM calorimeter</strong></td>
<td>Pb+LAr</td>
<td>PbWO4 crystals</td>
</tr>
<tr>
<td></td>
<td>$\sigma/E \approx 10%/\sqrt{E} + 0.007$</td>
<td>$\sigma/E \approx 2-5%/\sqrt{E} + 0.005$</td>
</tr>
<tr>
<td><strong>Hadronic calorimeter</strong></td>
<td>Fe+scint. / Cu+LAr (10(\lambda))</td>
<td>Cu+scintillator (5.8(\lambda) + catcher)</td>
</tr>
<tr>
<td></td>
<td>$\sigma/E \approx 50%/\sqrt{E} + 0.03$ GeV</td>
<td>$\sigma/E \approx 100%/\sqrt{E} + 0.05$ GeV</td>
</tr>
<tr>
<td><strong>Muon</strong></td>
<td>$\sigma/p_T \approx 2%$ @ 50 GeV to 10% @ 1 TeV (ID+MS)</td>
<td>$\sigma/p_T \approx 1%$ @ 50 GeV to 5% @ 1 TeV (ID+MS)</td>
</tr>
<tr>
<td><strong>Trigger</strong></td>
<td>L1 + Rot-based HLT (L2+EF)</td>
<td>L1+HLT (L2 + L3)</td>
</tr>
</tbody>
</table>
CMS Particle Detection

Key:
- Blue: Muon
- Red: Electron
- Green: Hadron (e.g. Pion)
- Dashed: Photon

Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid

Iron return yoke interspersed with Muon chambers

Transverse slice through CMS
reduce rate from 20 million collisions per bunch crossings / s ($10^9$Hz) to a few 100Hz
production rate for a light Higgs boson is about 0.1Hz
data reduction done in stages: trigger(HW) / filter(SW)
critical component of the experiment!
Event Selection Stages

**LEVEL-1 Trigger**
- Hardwired processors (ASIC, FPGA)
- Pipelined massive parallel

**HIGH LEVEL Triggers**
- Farms of processors

**Reconstruction & Analysis**
- TIER0/1/2 Centers

**ON-line vs OFF-line**
- 25ns
- 3µs
- ms
- sec
- hour
- year

**Rate vs Event Rate**
- barn
- mb
- nb
- µb
- gb
- pb
- fb

**Time Scales**
- 10⁻⁹
- 10⁻⁶
- 10⁻³
- 10⁻⁰
- 10³
- 10⁶
- 10⁹

**Events vs Mass**
- jet E_t or particle mass (GeV)
Experimental Challenges

Multiple collisions generates in average 25 events per bunch crossing!

Reconstruction of the 100s of charged particles in the high-granularity silicon tracking device
Higgs Production Modes @ LHC

Production % @125GeV

“gluon fusion” (ggF): ≈87.5%

“vector boson fusion” (VBF): ≈7%

“associated production” (VH): ≈5%

“tt fusion”: <1%

LHC Higgs XSWG:
Main contributions:

Low mass: $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ$ and $H \rightarrow WW$

Intermediate/high mass: $H \rightarrow WW_{\ell\ell}$ and $H \rightarrow ZZ$ (clean leptonic decay signatures)

LHC Higgs XS WG:

arXiv:1101.0593,
arXiv:1201.3084,
arXiv:1209.0040
Channel Characteristics

- The decay branching ratio determines the $m_H$ range where a channel is significant
- Final state objects determine the channel resolution for $m_H$

\[
m_H = \sqrt{E_H^2 - \vec{p}_H^2} = \sqrt{\sum E_i^2 - \sum \vec{p}_i^2}
\]

<table>
<thead>
<tr>
<th>Channel</th>
<th>$m_H$ range (GeV/c$^2$)</th>
<th>Data used</th>
<th>$m_H$ resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>110-150</td>
<td>5.1+19.6</td>
<td>1-2%</td>
</tr>
<tr>
<td>$H \rightarrow$ ta$t\tau$</td>
<td>110-145</td>
<td>4.9+19.6</td>
<td>15%</td>
</tr>
<tr>
<td>$H \rightarrow$ b$b$</td>
<td>110-135</td>
<td>5.0+19.0</td>
<td>10%</td>
</tr>
<tr>
<td>$H \rightarrow$ WW $\rightarrow$ l$\nu$l$\nu$</td>
<td>110-600</td>
<td>4.9+19.5</td>
<td>20%</td>
</tr>
<tr>
<td>$H \rightarrow$ Z$Z$ $\rightarrow$ 4l</td>
<td>110-1000</td>
<td>5.1+19.6</td>
<td>1-2%</td>
</tr>
</tbody>
</table>
Understanding the Backgrounds

- Validate and tune MC simulations on production cross section measurements
- All theoretical expectations calculated at NLO or higher
Standard Candles: $Z, J/\psi, \Upsilon$ decays

- $Z, J/\psi, \Upsilon \rightarrow l^+l^-, \gamma\gamma$ decays in data are standard candles to calibrate photon, electron and muon energy scales.
- Large source of clean events with well described mass peak.
- Energy measurements are corrected to match mass distributions between data and MC.

![Graph showing ATLAS and CMS data](image)

$\int L \, dt = 20.3 \, \text{fb}^{-1}$
High Resolution Channels

- Only high resolution physics objects (no jets or neutrinos)
- Full reconstruction of final state (model independence)

<table>
<thead>
<tr>
<th>Channel</th>
<th>BR(mH=125GeV)</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow ZZ \rightarrow 4l$</td>
<td>0.0276%</td>
<td>1-2%</td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>0.228%</td>
<td>1-2%</td>
</tr>
<tr>
<td>$H \rightarrow Z\gamma \rightarrow 2l\gamma$</td>
<td>0.01%</td>
<td>1-2%</td>
</tr>
<tr>
<td>$H \rightarrow \mu\mu$</td>
<td>0.0219%</td>
<td>1-2%</td>
</tr>
</tbody>
</table>
H→ZZ*→4ℓ

The Higgs golden channel

Signatures:
- two electrons or muons pairs, isolated from hadronic activity and categorized in: 4e, 2e2µ, 4µ
- very high S/B ratio channel

Challenges:
- need high efficiencies for lepton reconstruction and ID
- small branching fraction
- low Pt for at least 1 or 2 leptons (Z* yields low pT)

Methods:
- Z candidates formed from same-flavor & opposite-sign leptons
- FSR photon recovery to improve m_{ZZ} resolution
- For lepton pair closest to the Z-mass require: 40 (50) < m_{ll} < 120 (106) GeV CMS(ATLAS)
$H \rightarrow ZZ^* \rightarrow 4\ell$

Golden channel has clean experimental signature and allows full reconstruction of the final state

signal $H \rightarrow ZZ^* \rightarrow 4\ell$

irreducible background
$(qq \rightarrow Z\gamma^*, qq \rightarrow ZZ, gg \rightarrow ZZ)$

reducible background
$(Z+jets, \text{ttbar}, Z+\gamma+jets, WZ+jets, ...)$
Mass spectra shows a clean signal peak at ~126 GeV and very good control of the dominant ZZ background
Matrix Element Likelihood Analysis (MELA) uses kinematic inputs to build a kinematic discriminant for signal to background discrimination using \{m_1,m_2,\theta_1,\theta_2,\theta^*,\Phi,\Phi_1\}

\[
MELA = \left[1 + \frac{\mathcal{P}_{\text{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\text{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}
\]
H → ZZ* → 4l (CMS)

Low mass region

- Largest signal observed @ 125 GeV
- Local significance 6.8 σ
- Expected significance 6.7 σ
- Fitted \( \mu = \sigma/\sigma_{SM} \) @ 125 GeV

High mass region

- SM Higgs excluded @95%CL: [130, 827] GeV

H→ZZ*→4l (CMS)

✦ Simultaneous fit across three final state categories

✦ Dominant systematic uncertainty due to lepton momentum scale (∼1-3% on mass peak).

✦ Systematics include acceptance and efficiency uncertainties for electrons and muons

\[ m_H = 125.59^{+0.43}_{-0.41} \text{ (stat)}^{+0.16}_{-0.18} \text{ (syst)} \text{ GeV} \]
Simultaneous fit across three final state categories ggH, qqH and VH

Significance of the observed peak is 6.6σ for the combined 7 TeV and 8 TeV data, to be compared with 4.4σ expected from SM Higgs boson production at this mass.
Signatures:

- two photons isolated from hadronic activity
- additional two tag jets in case of VBF production

Challenges:

- small peaking signal on a large falling background (BR~0.2%)
- discrimination from large jet related backgrounds
- photon energy resolution
- $\gamma \rightarrow e^+e^-$ conversions in the detector

Method:

- Categorize events with two high $P_T$ photons based on the properties of the di-photon pair

\[
m_{\gamma\gamma} = \sqrt{2E_1^{\gamma}E_2^{\gamma}(1 - \cos \theta)}
\]
**Signal \( H \rightarrow \gamma \gamma \)**

**Background composition:**
- Prompt-prompt (irreducible): \( pp \rightarrow \gamma \gamma \) (~70%)
- Prompt-fake (reducible): \( pp \rightarrow \gamma + \text{jet} \) (~30%)
- Fake-fake (reducible): \( pp \rightarrow \text{jet} + \text{jet} \) (<1%)

**Irreducible QCD background**

**Reducible background (Compton)**
$H \rightarrow \gamma \gamma$ (ATLAS)

- Signal (fit to MC)- sum of Gaussians or CB function
- background (data-driven) – “discrete profiling” or bias study methods

**PRD 90, 052004 (2014)**
Dedicated analysis for mass measurement with events are split into 10 event categories:

- converted/unconverted photons
- photon $\eta$
- diphoton $P_T$ transverse to thrust
- different S/B, resolution between the categories
- smallest energy scale systematics in highest resolution (central) categories
Largest signal observed around 125 GeV (standalone discovery)
Local significance 5.7 $\sigma$
Expected significance 5.2 $\sigma$
Fitted $\mu = \sigma/\sigma_{SM}$ at 125 GeV $\pm 1.14 +0.26 -0.23$
Many exclusive channels addressing all production modes
Untagged mode split into categories with decreasing s/b with MVA

Results of the fit for individual production modes:
Higgs Mass Combination


\[
m_H = 125.09 \pm 0.21 \text{ (stat)} \\
\pm 0.11 \text{ (scale)} \\
\pm 0.02 \text{ (other)} \\
\pm 0.01 \text{ (theory)} \text{ GeV}
\]

✦ Statistical uncertainty dominates
✦ Scale uncertainties larger than systematic
✦ Expect improvements with more data!
✦ Interference not included in theory uncertainty
Higgs Couplings

Higgs mass determines all its couplings under SM ⇒ test for deviations

ATLAS-CONF-2015-007


“Measurement of the Higgs boson mass from the Hγγ and H→ZZ*→4l channels in pp collisions at center-of-mass energies of 7 and 8 TeV with the ATLAS detector” - PRD 90, 052004 (2014)

“Measurement of the properties of a Higgs boson in the four-lepton final state” - CMS - PRD 89, 092007 (2014)

“Precise determination of the mass of the Higgs boson and tests of compatibility of its couplings with the standard model predictions using proton collisions at 7 and 8 TeV” - CMS - Eur. Phys. J. C 75 (2015) 212

“Observation of the diphoton decay of the Higgs boson and measurement of its properties” - CMS - EPJC 74 (2014) 3076
Low Resolution Channels

- Involves low resolution physics objects (jets and/or neutrinos)
- Incomplete reconstruction of final state (model dependence)

<table>
<thead>
<tr>
<th>Channel</th>
<th>BR(mH=125GeV)</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow bb$</td>
<td>57.7%</td>
<td>10%</td>
</tr>
<tr>
<td>$H \rightarrow \tau\tau$</td>
<td>6.32%</td>
<td>10-20%</td>
</tr>
<tr>
<td>$H \rightarrow WW \rightarrow 2l2\nu$</td>
<td>0.756%</td>
<td>20%</td>
</tr>
</tbody>
</table>
H→WW→lνlν

The most sensitive channel around 2xM_W

Signature:
- 2 high p_T isolated leptons
- large missing transverse energy due to neutrinos

Challenges:
- no mass peak!
- very good understanding of backgrounds: WW, W/Z +jets, top and Drell-Yan

Methods:
- Scalar Higgs + (V-A) favors small opening angles between leptons
- enhance sensitivity by subdividing into 0,1,2 jets categories

μ: 32 GeV
µ: 32 GeV

e: 34 GeV

MET: 47 GeV

H→WW*→eμν candidate and two jets with VBF topology

Longitudinal view

Projected η-φ view
Higgs decay kinematics => scalar decay and V-A structure of W decay lead to a small opening angle between leptons
$H \rightarrow WW \rightarrow l\nu l\nu$

Data driven background estimation
H→WW→lνlν (CMS)

- Events with 0- and 1-jet and different flavour leptons (7+8 TeV Data)
- A significant excess observed …

\[ M_T = \sqrt{2p_T^{\ell\ell} E_{T}^{\text{miss}} \cos(\Delta\phi_{\ell\ell} - E_{T}^{\text{miss}})} \]
$H \rightarrow WW \rightarrow l\nu l\nu$ (CMS)

- Several categories combined: 0jet, 1 jet, VBF, VH
- Broad evidence of signal around 125 GeV
- Expected (observed) significance: $5.8\sigma (4.3\, \sigma)$
- Fitted $\sigma/\sigma_{SM} = 0.72$
$H \rightarrow WW \rightarrow l\nu l\nu$ (ATLAS)

ATLAS results are very similar …

$\sigma/\sigma_{SM} = 1.09^{+0.16}_{-0.15} \text{ (stat.)} +0.17_{-0.14} \text{ (syst.)}$
$H \rightarrow \tau\tau$

Large rates with medium mass resolution

Signature:
- $e$, $\mu$, $\tau_H$ from tau decay
- MET from tau neutrinos

Challenges:
- Reconstruct corrected $\tau\tau$ invariant mass
- Separate the Higgs peak from the DY decay

Methods:
- Use many categories to increase the sensitivity
- Template fit of $m_{\tau\tau}$ shape
$H \rightarrow \tau\tau$ (CMS)

Complicated analysis, many different sub-channels

- 0-jet
- 1-jet boosted
- 2-jet VBF
- VH (use leptonic decays of V)

\[
\begin{align*}
H & \rightarrow \tau\tau \rightarrow \ell\ell + 4\nu \ (12\%) \\
H & \rightarrow \tau\tau \rightarrow \ell \tau_h + 3\nu \ (46\%) \\
H & \rightarrow \tau\tau \rightarrow \tau_h\tau_h + 2\nu \ (42\%)
\end{align*}
\]
H →ττ (CMS)

- Broad evidence of signal near 125GeV with expected (observed) significance: 3.2σ (3.7σ)
- Fitted signal strength σ/σ_{SM} = 0.78 ± 0.27
- Evidence of Higgs coupling to τ leptons!
$H \rightarrow bb$

QCD background too large so needs additional tag

**Signature:**
- b-jets identified through displaced tracks
- leptons and MET from b-decay

**Challenges:**
- largest number of Higgs decays but too much QCD background
- main backgrounds are W/Z+jets and top

**Methodology:**
- categorize in associated prod : VH, ttH
- go to high pT where Higgs is enhanced
- MVA based analyses to enhance sensitivity
S/B weighted mass distribution

Background subtracted (except VV)

Phys. Rev. D 89, 012003
VH , H→bb (CMS)

- Excess of events near 125 GeV
- expected(observed) significance: $2.1\sigma(2.1\sigma)$
- Fitted $\sigma/\sigma_{SM} = 1.0 \pm 0.5$
- Combined with $H\tau\tau$ gives $3.8\sigma$ significance ⇒ evidence of Higgs coupling to down type fermions  

NATURE PHYS. 10(2014)

Phys. Rev. D 89, 012003
Search for $ttH$ production in $Hbb$, $\gamma\gamma$, multi leptons

- Some excess of events near 125 GeV ($\sim 2\sigma$ above SM)
- Expected (observed) significance: $1.1\sigma (3.4\sigma)$
- Fitted $\sigma/\sigma_{SM} = 2.8 \pm 1.0$
- Excess driven by the same sign di-lepton search

JHEP 09 (2014) 087
High Mass SM Higgs Search

High mass search with channels WW & ZZ exclude a SM-like Higgs boson in the range $145 < m_H < 1000$ GeV
SM Higgs Properties

- All channels are combined
- Profile likelihood fits are carried out with all nuisances profiled
- Cross sections, branching ratios and recommendations taken from the LHC cross section WG:

  https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections
Higgs Signal Strength (CMS)

- Combined $\mu = \sigma/\sigma_{SM} = 1.00 \pm 0.09\text{(stat)} \pm 0.08\text{(theo)} \pm 0.07\text{(syst)}$
- Signal strengths in different channels and production modes are consistent with the SM
Higgs Couplings (CMS)

- Vector and fermion couplings are scaled by factors $k_f$ and $k_v$
- Couplings are proportional to particle masses as expected in SM
- Results agree with SM within $\sim 1\sigma$

Higgs Signal Strength and Couplings (ATLAS)

✦ Summary of the signal-strength measurements, as published, from individual analyses
✦ Coupling scale factors for fermions and bosons, assuming only SM contributions to the total width

ATLAS-CONF-2015-007
Higgs Off-shell Analysis (ATLAS)

Measure Higgs signal strength for $m_{VV} >> 2M_V$ $(V=W,Z)$ and look for couplings deviations at high energies.

Considered the decay channels $ZZ\rightarrow 4l$, $ZZ\rightarrow 2l2v$ and $WW\rightarrow 2l2v$. 

![Graphs showing analysis results](image)
Higgs Off-shell Analysis (ATLAS)

Assume SM value for signal strengths off-shell ratio for $\mu_{ggH}/\mu_{qqH}$

<table>
<thead>
<tr>
<th>$R^B_{H^*}$</th>
<th>Observed</th>
<th>Median expected</th>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>5.1</td>
<td>6.7</td>
<td>$\mu_{gg\to H^*}/\mu_{VV} = 1$</td>
</tr>
<tr>
<td>1.0</td>
<td>6.2</td>
<td>8.1</td>
<td>$\mu_{off-shell}/\mu_{VBF\to VV} = 1$</td>
</tr>
<tr>
<td>2.0</td>
<td>8.6</td>
<td>11.0</td>
<td></td>
</tr>
</tbody>
</table>

Expected with syst. | Expected no syst. | Observed with syst. | Observed no syst.

$\sqrt{s} = 8$ TeV: $\int L dt = 20.3$ fb$^{-1}$


Observed(expected) 95% CL upper limits on $\Gamma_H/\Gamma_H^{SM} < 5.5(8.0)$ for the combined off-shell ZZ and WW analyses
Custodial Symmetry Test

Modify the SM Higgs boson couplings to the W and Z bosons introducing two scaling factors $k_W$ and $k_Z$ and perform combinations to assess if $\lambda_{WZ} = k_W/k_Z = 1$.

95% CL interval for $\lambda_{WZ}$: [0.62, 1.19]
Statistics In Nutshell: Exclusion, Evidence & Discovery

H0: null hypothesis (ex: no Higgs)
H1: alternate hypothesis (ex: existence of the Higgs)

Quantify the level for which the hypotheses are accepted or rejected

- Confidence level for the exclusion:
  - significance < 3σ

- Signal significance (p-value):
  - 3σ =< significance < 5σ → evidence
  - significance >= 5σ → discovery
Higgs Boson Spin-Parity

- The spin-parity of the Higgs boson candidate can be probed using angular distributions
- Mainly use diboson channels $H \rightarrow ZZ$ and $H \rightarrow WW$
- The presence of the $H \rightarrow \gamma\gamma$ decay excludes the spin 1 hypothesis (Yang’s Theorem)
- Hypothesis testing is performed for different alternatives: spin 0, spin 1 and spin 2

RESULTS:
- Strong exclusion of a spin 1 resonance
- Spin 0 excluded at $>3\sigma$ level
- Graviton like resonances excluded at $>3\sigma$
Higgs Boson Spin-Parity (CMS)

Spin-parity measurement with **Matrix Element Likelihood Analysis** (MELA)

\[
\text{MELA} = \left[ 1 + \frac{P_{\text{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1|m_{4\ell})}{P_{\text{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1|m_{4\ell})} \right]^{-1}
\]
Higgs Boson Spin-Parity (ATLAS)

- Uses the decay angles and invariant masses, combined to build a BDT discriminant
- Distributions of the test statistic $\tilde{q}$ for the SM Higgs boson and for the JP alternative hypotheses favors the former
Higgs Width from off-shell ZZ

- Direct measurement limited by experimental mass resolution $O(2\text{GeV})$ while SM expectation $\Gamma_{H_{125}} = 4 \text{ MeV}$
- Narrow width approximation not adequate for Higgs to VV. Off-shell contribution is sizeable at high ZZ mass (~7.6% cross section increase)


- From cross section ratio derive width information
- Assume couplings are unchanged between on-shell and off-shell  
  F. Caola, K. Melnikov (Phys. Rev. D88 2013, 054024)
Higgs Width from off-shell ZZ (CMS)

- Use MELA for $ggZZ$ and $qqZZ$ discrimination including interference
- 2D likelihood analysis using discriminator versus $m_{4l}$ for separating on-shell and off-shell regions

\[
\text{Observed(expected) @ 95\% C.L : } \Gamma_H < 4.2(8.5) \Gamma_{HSM}
\]

Under the peak  Far from the peak (>220GeV)  Phys. Lett. B 736 (2014) 64
BSM Searches

All searches correspond to looking for discrepancies between predicted and observed distributions!
Higgs to Invisibles

The Higgs boson could decay to invisible particles, such as dark matter candidates. Exploit VBF qqH and ZH with Zll(bb) production modes.

Higgs to Invisibles

No signal observed and limits are derived. Combined exclusion and Dark Matter interpretation...

Combined observed (expected) limit:
\[ \text{BR}(H_{\text{inv}}) < 0.58 \ (0.44) \text{ @ 95\% CL} \]

These limits can be interpreted in a Higgs portal model in which the DM couples to the Higgs.
Search for the resonant production of two Higgs bosons from radion or graviton decay
X → HH

No signal observed, derive limits on $\sigma\cdot BR$, assuming $BR(X\rightarrow HH)=25\%$ for this plot.

Complementary: $bb\gamma\gamma$ more sensitive at lower masses, $4b$ at higher masses
Atlas event selected by the WW, WZ and ZZ cuts, with dijet invariant mass $m_{jj}=2.0\text{ TeV}$. Leading jet has $P_T=1.1 \text{ TeV}$ and $m_j=93.7 \text{ GeV}$ while subleading jet has $p_T=0.9\text{ TeV}$ and $m_j=92.8\text{ GeV}$.
Search for high mass diboson resonances with boson tagged jets (W/Z jets)

- Fat jets reconstructed using the Cambridge–Aachen (C/A) algorithm with a radius $R = 1.2$
- Fat Jets are then groomed to reduce pile-up contribution and identify the subjets pair associated with the boson decays: $W \rightarrow q\bar{q}q'$ or $Z \rightarrow q\bar{q}$
- Selected subjets are then filtered: the original topological cluster constituents of that pair taken together and clustered using the C/A algorithm with a small radius $R = 0.3$
- Filtered jets are calibrated using $(E, \eta)$ dependent correction from simulation. The calibrated jet 4-momentum is used as the $W$ or $Z$ boson 4-momentum
- Narrow mass windows of 26 GeV chosen to optimise sensitivity to signal events and are centred at either $M_W = 82.4$ GeV or $M_Z = 92.8$ GeV, which is where simulation peaks
High Mass Di-boson Search (ATLAS)

High-mass resonances decaying to a pair of boosted vector bosons. The subsequent bosons hadronic decay are recognized as two large-radius massive jets with large momentum, typically balanced in pT.

Selection Cuts:

✦ ungroomed jet Pt greater than 540 GeV.
✦ no electron with ET > 20 GeV with |\eta| < 1.37 or 1.52 < |\eta| < 2.47
✦ no muon with pT>20GeV in the region |\eta| <2.5
✦ leading jets must have |\eta|<2.0 and |\Delta\eta|<1.2
✦ leading jets satisfy boson tag |m_{j}-m_{V}|<13 GeV

![Graph of jet distribution]
High Mass Di-boson Search (ATLAS)

- Signal significance (p-value) for WZ, WW and ZZ selections
- Dijet mass distributions with bin by bin significance compared with EGM(SSM) W' model
High Mass Di-boson Search (ATLAS)

Exclusion limits @ 95%CL on the $\sigma$.BR for:

- WZ final state of a new heavy gauge boson $W'$ with couplings of EGM(SSM) model in the mass range [1.3,1.5] TeV

- WW and ZZ final states of Kaluza–Klein excitations of the graviton in a bulk RS model
High Mass Di-boson Search (CMS)

Search for new resonances decaying to WW, ZZ or WZ in which sub-sequentially one of the vector bosons decays leptonically and the other hadronically.

- Non-resonant W jets background prediction extracted from a fit to the side bands.
- MC resonant shapes are corrected using the differences between data and simulation in the W peak position and width measured in the control region.
- A jet is identified as W-jet if its pruned mass falls in the range [65,105]GeV and similarly a Z-jet is required to have a pruned mass in [70,110]GeV.
- Reject V jet candidates with $\tau_{21} > 0.7$ because jets coming from hadronic W/Z decays are characterized by lower values of $\tau_{21}$ compared to the SM backgrounds.
Upper limits at 95% confidence level are set on the Bulk Graviton model production cross for resonance masses between 600 and 2500 GeV.
**Run 2 and Beyond**

**Run2 Start on June/03, 2015, with stable beams @6.5TeV**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Days</td>
<td>MAM</td>
<td>MAM</td>
<td>MAM</td>
<td>MAM</td>
<td>MAM</td>
<td>MAM</td>
<td>MAM</td>
<td>MAM</td>
<td>MAM</td>
</tr>
<tr>
<td>Efficiency</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Int.Lumi</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Initial Low Lumi**: 7 days, 20% efficiency, ~ few pb-1
- **50ns**: 21 days, 20% efficiency, ~ 0.5 fb-1
- **25ns**: 70 days, 30% efficiency, ~ 8 fb-1

![CMS Experiment at the LHC, CERN](image.png)

- Data recorded: 2015-Jun-03 08:48:32.276562 GMT
- Run / Event: LS: 246988 / 77814059 / 86
LHC Luminosity Evolution

Run1
- E: 13TeV
- PU: 40
- BS: 50-25ns
- L: 100fb⁻¹

Run2
- PU: 60
- BS: 25ns
- L: 100fb⁻¹

Run3
- PU: 140
- L: 3000fb⁻¹

HL-LHC

Year

Luminosity [cm⁻²s⁻¹]
8TeV→13TeV : What Changes ?

ratios of LHC parton luminosities: 13 TeV / 8 TeV

In gg fusion:
- for $s = 1$ TeV, x6
- for $s = 2$ TeV, x15
- for $s = 3$ TeV, x45
- for $s = 4$ TeV, ~x200

In qq, ~x2 less

MSTW2008NLO

Minimum bias
- ZZ 2.1
- WH 2.1
- H (ggF) 2.6
- H (VBF) 2.6
- tt 3.9
- ttH 4.7

Stop pair
- (0.7 TeV) 11 (for 13 TeV / 8 TeV: 8.4)
- (0.9 TeV) 16 (for 13 TeV / 8 TeV: 12)

Gluino pair
- (1.5 TeV) 72 (for 13 TeV / 8 TeV: 46)
- (2.5 TeV) 5700 (13 / 8: 2700)

Z' SSM (3 TeV) 13
Q* (4 TeV) 87
QBH (6 TeV) 12000
Higgs Production (13TeV)

- SM Higgs is light, so the gluon fusion cross section doesn’t get that much boost ($x2, 19.1 \rightarrow 43.6$ pb)
- Background cross sections also increase

<table>
<thead>
<tr>
<th>$\sigma$ [pb] at $m_H=125.5$ GeV</th>
<th>8 TeV</th>
<th>13 TeV</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>ggF</td>
<td>19.1</td>
<td>43.62</td>
<td>2.6</td>
</tr>
<tr>
<td>VBF</td>
<td>1.6</td>
<td>3.727</td>
<td>2.6</td>
</tr>
<tr>
<td>WH</td>
<td>0.7</td>
<td>1.362</td>
<td>2.1</td>
</tr>
<tr>
<td>ZH</td>
<td>0.4</td>
<td>0.8594</td>
<td>2.1</td>
</tr>
<tr>
<td>ttH</td>
<td>0.1</td>
<td>0.5027</td>
<td>4.7</td>
</tr>
</tbody>
</table>
Higgs Physics Prospects

Run 2 and 3 (starting in 2015):
- Re-discovery of the Higgs
- Measure Higgs properties
  - cross section (also differential)
  - mass & width
  - couplings to bosons, fermions, ttH & EFT
- Searches for BSM Higgs
  - additional boson in EWK singlet model
  - search for $H \rightarrow hh$ and $A \rightarrow Zh$ in 2HDM
  - search for $H^+$, dark matter

High Luminosity-LHC (from 2025):
- Precision measurements (2x improvement)
- Searches for
  - rare decays,
  - anomalous couplings
  - CP-violation in Higgs
- Search for BSM decays
  - invisible
  - $t \rightarrow cH$
- $VV$ scattering
- HH production & self-coupling
Higgs Signal Strength (300fb\(^{-1}\))

Higgs signal strength \(\mu = \sigma / \sigma_{SM}\) with 300 fb\(^{-1}\) gives 2x factor improvement in precision measurement.

**CMS:**
- Extrapolated from 2011/12 results
- Scenario 1 and 2 \(\approx\) upper and lower bounds
- Precision of 6-14\% on \(\mu\)

**ATLAS:**
- Based on parametric simulation
- Precision of 6-20\% on \(\mu\)
- Hbb not yet included
Higgs Couplings (300fb$^{-1}$)

Assumes no extra BSM Higgs decays so absolute couplings can be extracted and minimal coupling fit.

**CMS:**
- uncertainties on $K_i$ limited by theoretical uncertainties on production and decay rates
- $\sigma (\kappa_Y) \approx 3$-$6\%$  \  $\sigma (\kappa_F) \approx 5$-$15\%$

**ATLAS**

\[
\begin{array}{c|c|c|c|c}
\text{Nr.} & \text{Coupling} & \text{300 fb}^{-1} \text{ Theory unc.:} \\
& & \text{All} & \text{Half} & \text{None} \\
2 & \kappa_Y = \kappa_Z = \kappa_W & 3.3\% & 2.8\% & 2.7\% \\
& \kappa_F = \kappa_t = \kappa_b = \kappa_T = \kappa_\mu & 8.6\% & 7.5\% & 7.1\% \\
\end{array}
\]
Higgs Partial Width Ratios (300fb$^{-1}$)

No assumption on the total Higgs width. Take ratios so many experimental and theoretical uncertainties cancel.

CMS:
With 300 fb-1 the uncertainties on the Higgs coupling scale factor ratios are expected in the range 4-15%
Higgs Mass (300 fb\(^{-1}\))

- Increase in Higgs cross section (2x) from 8 TeV to 14 TeV, the statistical uncertainty is expected to be reduced to:
  - 50 MeV with 300 fb\(^{-1}\)
  - 15 MeV with 3000 fb\(^{-1}\)
- Precision of the future measurement will likely be dominated by systematics.
- Energy/momentum scale of photons, electrons and muons should improve with increasing statistics.
- Making optimistic assumption that systematics also scales with statistics, the expected systematic uncertainty is:
  - 70 MeV with 300 fb\(^{-1}\)
  - 25 MeV with 3000 fb\(^{-1}\)
- ATLAS 1999 TDR estimates that a relative precision of 0.07\% is achievable with 300 fb\(^{-1}\)
- CMS 2007 TDR projects a statistical uncertainty of 0.1\% with 300 fb\(^{-1}\)
Invisible Higgs (300 fb$^{-1}$)

Invisible Higgs can be seen as as a portal to Dark Matter

- **Indirect constraints:**
  - from Higgs coupling fit
  - BR(H->inv) < 28% @ 95% CL

- **Direct search:**
  - ZHee/µµ+ETmiss
  - BR(H->inv) < 32% @ 95% CL

- Possible to convert the limits on BR(Hinv) into the strength of the interaction between dark matter and Higgs boson, $\lambda_{H\chi\chi}$

- Bound on $\lambda_{H\chi\chi}$ can be mapped into scattering cross section of dark matter on a nuclei

- Limits from ATLAS at low mass better than those from direct detection limits degrade as $m_\chi$ approaches $m_H/2$
VV Scattering (3000 fb$^{-1}$)

HighWithout the Higgs, $W_L W_L \rightarrow W_L W_L$ violates unitarity at $\sqrt{s} \sim O(1 \text{ TeV})$

✦ $W, Z$ masses (longitudinal degrees of freedom) arise from the Higgs mechanism
✦ Higgs exchange diagrams cancels the divergence making the amplitude finite.
✦ Complementary to Higgs coupling analysis

\[ A(W_L^+ W_L^- - W_L^+ W_L^-) \approx \frac{1}{v^2} \left( -s - t + \frac{s^2}{s - m_H^2} + \frac{t^2}{t - m_H^2} \right) \]
VV Scattering: Interference

Large interference between signal and irreducible background!

Need to use the full set of diagrams (signal + irr. background) and impose kinematics cuts to isolate phase space regions where signal dominates over background.
VV Scattering as a EWSB probe

VV Scattering spectrum, $\sigma(VV\rightarrow VV)$ is a fundamental probe to test the nature of the Higgs boson and EWSB

- Some BSM models predict TeV resonances “paired” with a light scalar particle ($H_{125}$) ⇒ search for resonances in VBF spectrum
- Contrary to what one expects LL does not dominate at high $m_{VV}$, but angular analysis can help …
VV Scattering as a EWSB probe

VV Scattering expectations in the fully leptonic mode for 300 and 3000 fb$^{-1}$

- **Very low cross section** (in 20 fb$^{-1}$
  CMS expects 0.1 signal events >1 TeV)
- **Main background is VV+jets**
- **Sensitivity to anomalous couplings in VBS**
- **HL-LHC should be able to provide answers to most benchmark cases.**

![Graph showing ATLAS Preliminary results](image)

<table>
<thead>
<tr>
<th>model</th>
<th>300 fb$^{-1}$</th>
<th>3000 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{\text{resonance}} = 500$ GeV, $g = 1.0$</td>
<td>2.4σ</td>
<td>7.5σ</td>
</tr>
<tr>
<td>$m_{\text{resonance}} = 1$ TeV, $g = 1.75$</td>
<td>1.7σ</td>
<td>5.5σ</td>
</tr>
<tr>
<td>$m_{\text{resonance}} = 1$ TeV, $g = 2.5$</td>
<td>3.0σ</td>
<td>9.4σ</td>
</tr>
</tbody>
</table>
Conclusions

• The discovery of the new particle has been confirmed with more data. Now measuring its properties.

• The spin/parity is compatible with a 0+ state (scalar)!

• Mass of the new particle is $m_H = 125.1 \pm 0.2$ GeV

• Decays into fermion (τ+b channels) observed with combined significance > 3σ

• Search for rare decays & processes is going on…

• The couplings to bosons and fermions consistent with SM at ~20-30% precision level => Surprises still possible !!!

• A new energy domain with a vast potential for new physics discoveries and precision measurements will open with the Run 2 and Run 3 at $\sqrt{s} = 13$ TeV

• Similar results and projections from ATLAS and CMS in spite of the differences in the assumptions